NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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EFFECTS OF MODERATE BIAXIAL STRETCH-FORMING ON TENSILE AND CRAZING PROPERTIES OF ACRYLIC PLASTIC GLAZING

By B. M. Axilrod, M. A. Sherman, V. Cohen, and I. Wolock
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SUMMARY

The effects of approximately 50-percent biaxial stretch-forming on the tensile and crazing properties of polymethyl methacrylate were investigated. The materials used were commercial cast polymethyl-methacrylate sheets, nominally 0.15 inch thick, of both general-purpose and heat-resistant grades. Portions of the sheets were biaxially stretch-formed by means of a vacuum forming vessel, which had been designed to produce flat uniformly stretched disks of 10-inch diameter. Specimens from the formed pieces as well as from the unformed portions of the same sheets were subjected to various tests including standard tensile, stress-solvent crazing with benzene, long-time tensile loading, and accelerated weathering.

The results indicate that biaxially stretch-forming polymethyl methacrylate approximately 50 percent does not affect its tensile strength or secant modulus of elasticity in tension. However, the total elongation and the stress and strain at the onset of crazing in the short-time tests were greatly increased by the stretch-forming. The forming also increased the threshold stress of stress crazing about 40 percent for loading times up to 7 days and increased the threshold stress of stress-solvent crazing with benzene about 70 to 80 percent. It was observed in the long-time tensile tests that the crazing cracks were more closely spaced and finer on formed as compared with unformed specimens.

INTRODUCTION

Although polymethyl-methacrylate glazing in aircraft is frequently prepared by a forming process which stretches the material, there is little information reported on the effect of this stretching on the tensile and crazing properties of the material. Some data of this type were obtained at Northrop Aircraft, Inc. (reference 1). Tensile tests were made on specimens taken from pieces of polymethyl methacrylate that had been stretched uniaxially. The pieces were stretched about 60 percent while at 265° F and cooled while held at this elongation. It was found that at both room and sub-zero temperatures the specimens oriented transversely to the direction of stretch were appreciably weaker than the longitudinal specimens; also at room temperature the latter specimens showed appreciable permanent set in contrast to the former.

The effects of hot-stretch-forming on polystyrene, a material somewhat similar to polymethyl methacrylate in forming behavior, have been reported by Bailey (reference 2). It was found that uniaxial stretching of several hundred percent greatly increased the tensile strength, the elongation at failure, and the "crazing strength"[1] in the direction of stretch; the tensile strength was greatly reduced perpendicular to the direction of stretch. Also the tensile strength of sheets hot-stretched first longitudinally and then transversely roughly 200 percent was reported as greatly increased for both directions.

The experiments that are described in this report were made to gain more information on the effect of forming on the crazing and other properties of polymethyl methacrylate. The properties determined on both formed and unformed pieces of sheet material included tensile strength, total elongation, strain and stress at the onset of stress crazing, threshold stress for stress-solvent crazing, and resistance to weathering.

The major portion of the work was done on material stretched biaxially to an elongation of about 50 percent; that is, about 50 percent in all directions. A few experiments were also made on pieces stretched slightly, about 7 to 20 percent. This work was carried out as one phase of a research program whose purpose is to investigate factors affecting the crazing and strength properties of laminated acrylic glazing. The research is being done at the National Bureau of Standards under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

The courtesy of E. I. du Pont de Nemours & Co., Inc., and the Rohm & Haas Co., Inc., in furnishing material for use in this investigation and of the Lockheed Aircraft Corporation for testing some pieces formed in this laboratory is gratefully acknowledged. The authors also greatly appreciate the advice and information received from Mr. R. E. Leary and Mr. W. F. Bartoe of the two companies, respectively, and from Mr. Wendell Koch of the Air Materiel Command. The assistance of

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[1]In reference 2 the test conditions were not indicated nor was it specified whether the "crazing strength" was a stress-crazing or a solvent-crazing threshold.

Mr. M. N. Geib, who designed the long-time loading apparatus, of Mr. A. Pennington, who did much of the construction of the equipment, and of Mr. John Mandel, who advised on statistical matters, is also acknowledged.

MATERIALS

The materials used were commercial cast polymethyl-methacrylate sheets approximately 0.12 to 0.15 inch in thickness. The samples used for all experiments except the exploratory work were obtained directly from the manufacturers and were masked on one side only, as is done for sheets used to make laminated acrylic glazing. These samples, which included both the general-purpose grade and the heat-resistant grade (defined in reference 3), consisted of one 36- by 48- by 0.15-inch sheet from each of three production runs. They are referred to subsequently as "representative" samples and are identified as follows:

NBS sample	Material	Grade	Date received
L1d	Lucite HC201	General purpose	9/49
L2d	Lucite HC202	Heat resistant	9/49
P1a	Plexiglas I-A	General purpose	10/49
P2a	Plexiglas II	Heat resistant	10/49

APPARATUS AND PROCEDURE

Forming Process

Equipment and procedure.- A vacuum forming apparatus which would produce flat biaxially stretched disks about 10 inches in diameter was designed following suggestions offered by Mr. W. F. Bartoe of the Rohm & Haas Co., Inc.

A schematic diagram of the forming equipment is shown in figure 1. In this apparatus a sheet of acrylic material A heated to the rubbery state is clamped to the flange of the cylindrical forming vessel B.

A partial vacuum is created in the vessel by connecting the latter to an evacuated tank. The pressure differential, controlled by the plug valve C, draws the unclamped part of the sheet into the vessel. The form D, an open-end cylindrical tube a little smaller in diameter than the forming vessel and constrained by the guide E, is inserted into the vessel. The pressure differential is then removed quickly by admitting air through the plug valve F, so that the stretched acrylic sheet shrinks about the end of the form. The sheet cannot retract completely; the central portion remains uniformly stretched across the open end of the form. The formed acrylic sheet, shaped like a top hat, is cooled to room temperature in the vessel before removal.

In practice, the forming operation is done as quickly as possible so that the acrylic sheet will still be in the rubbery state when the pressure differential is removed; the time from removal of the sheet from the oven until forming is complete is less than 1 minute. As an additional aid to forming, the flange of the forming vessel, a ring of 0.5-inch-thick paper-base phenolic laminate, is preheated with infrared lamps; this keeps the portion of the acrylic sheet near the clamped edge in a rubbery state.

The forming apparatus is shown in figures 2 and 3 after the following modifications were made to permit much deeper drawing: (1) The flange was built up with plywood to prevent the formed sheet from striking the bottom. (2) The entire forming vessel was heated through a flexible pipe coupled to the oven in which the acrylic sheet was heated; the pipe, as shown in figure 2, was attached inside the form so that during the forming operation hot air would be directed against the center of the sheet to prevent it from cooling too rapidly. (3) A flexible pipe, preheated in the oven, was attached to the air inlet of the forming vessel so that, when the vacuum was dissipated, the incoming air would not chill the stretched acrylic sheet.

Uniformity of forming and equation for elongation.- To determine whether the amount of stretching is uniform over the face of the biaxially stretched pieces, the following experiments were made: A 10-inch disk of Lucite HC201, which had been biaxially stretched 150 percent after heating to 140° C, was marked off in 1-inch squares, then heated to 140° C, and allowed to assume its original size. The lines on the resulting disk were still equidistant within ± 5 percent. Since the standard deviation of the measurement and marking errors was also of this order of magnitude, this indicates that the amount of stretching was reasonably uniform over the face of the disk. Next, another piece of Lucite HC201 was marked with a square grid having a spacing of 15 millimeters; the piece was then biaxially hot-stretched to an elongation of 150 percent. The lines on the flat top of the stretched dome were still equidistant to within ± 5 percent, the experimental accuracy, verifying that the stretching was reasonably uniform.

The formula used for calculating the amount of biaxial stretching in a formed disk is

$$e = 100\left(\sqrt{t_i/t_f} - 1\right) \qquad (1)$$

where e is the elongation in percent and t_i and t_f are the initial and final thicknesses, respectively. This formula is based on the fact that the volume of the material remains essentially constant on stretching.

This property of the materials was verified by measuring the density of a small piece of both 160-percent-formed and unformed material from each of the four samples. The sample of Lucite HC201 showed a decrease in density of 0.8 percent as a result of forming to 160-percent strain. The other three samples showed density changes of less than 0.2 percent as a result of this amount of stretch-forming.

Standard Tensile Test

The standard tensile tests were made following in most details Method No. 1011 of Federal Specification L-P-406a. The testing machine used was a 2400-pound-capacity Baldwin-Southwark hydraulic universal testing machine. Autographic load-elongation records were obtained with a nonaveraging Southwark-Peters extensometer, Model PS-6, coupled to the associated recorder on the testing machine. In these tests the threshold of stress crazing was noted visually by an observer who immediately applied a sudden momentary pressure to the sensitive cross head to cause a jog in the load-elongation record. The strain and the stress at this threshold could thus be readily obtained from the record. The observer viewed the crazing against a dark background using north daylight or fluorescent light.

The cross-head speed was 0.05 inch per minute up to 10-percent elongation; the strain gage was removed at this point and the speed increased to 0.25 inch per minute with further elongation measured with dividers.

The specimens were tested in the standard atmosphere, 23° C and 50-percent relative humidity, after conditioning 2 weeks in this atmosphere.

Stress-Solvent Crazing Test

In the stress-solvent crazing tests, tapered tensile specimens of the same dimensions as the long-time tensile test specimens described in the next section were placed under load in the hydraulic testing machine, benzene applied, and the load maintained for 4 minutes. From preliminary trials on other specimens, the loads on these specimens were selected to produce crazing over a part of the tapered portion. The two specimens of each formed or control piece were tested with slightly different loads in an effort to locate the threshold at different parts of the tapered portion of the specimen.

The benzene was applied to the specimen as follows: A controlled amount of benzene, 0.03 to 0.04 gram, was put on a No. 1 camel's hair brush (about 0.1 in. in diameter and 0.5 in. long) from a marked glass dropper. The central 1/4- by 3-inch portion of the specimen was stroked with the brush until the latter was dry. Subsequently, the solvent-crazed specimens were examined under suitable lighting and the extent of the crazing noted.

The stress-solvent crazing tests were made in the standard atmosphere, 23° C and 50-percent relative humidity, on specimens conditioned at least 1 week in this atmosphere.

Long-Time Tensile Test

The long-time tensile-loading cabinet for testing at high (about 95-percent) relative humidity is shown in figures 4 and 5. A similar cabinet without a front cover or blower and with an interior instead of exterior light was used for tests at 50-percent relative humidity, the condition in the controlled-atmosphere room in which the cabinets were located.

In each cabinet four specimens can be tested simultaneously. The load on the specimen is applied by a 300-pound-capacity weigh beam through a turnbuckle. A pair of alinement holes in each end of the specimen and an alinement hole and an alinement pin in the clamp, as shown on the specimen at the left of figure 4, facilitate alining the clamps and specimen. The specimen is fastened to the clamps and then put in place in the loading frame. The load is applied through an S-hook on the bottom clamp and a thin metal strap at the top clamp. The load in the specimen is made axial as follows: With a light load on the specimen, the strap and the S-hook are shifted laterally on their respective loading pins until a straightedge indicates the clamps are parallel. The full load is then applied and the parallelism of the clamps checked and adjustments made if necessary. The alinement details are critical as otherwise stress crazing occurs much sooner on one face than on the other or along one edge rather than across the width of the specimen.

The humidity cabinet (fig. 4) has a blower which, for 95-percent relative humidity, directs air against cloth wicks dipping into a tray of water. If low humidity is desired, the water tray and wicks can be replaced with trays of silica gel. The relative humidity is readily measured with wet- and dry-bulb thermometers placed near the exhaust part of the blower (see fig. 4). The relative humidity is maintained at 95 ± 2 percent.

To prevent the air temperature from rising more than a fraction of a degree above the temperature of the room, it is necessary to operate the blower intermittently; in practice an automatic controller turns it on for about 10 seconds once a minute. Also to avoid heating of the cabinet, the fluorescent lights used for observing crazing are placed just outside a window in the top of the box. Mirrors, mounted behind and slightly above the specimens, direct the light against the latter which are viewed against a black felt background. For each weigh beam a time clock, controlled by a microswitch on the weigh-beam stop, serves to indicate either the time of failure or the time when the weigh beam rests on the stop because of specimen creep.

The tensile specimen used for the long-time loading tests had a 3-inch-long reduced section tapered uniformly in width from 0.50 inch at the maximum cross section to 0.33 inch at the minimum cross section. The radii at the ends of the reduced section were 3 inches. In this way the stress in the reduced section decreased from a value of σ_0 at the minimum section to $2/3\ \sigma_0$ at the other end. The time for the onset of crazing for different stresses was found by observing the specimen periodically and noting the extent of the crazing. Some of the details of the test procedure were as follows. The specimens being tested were observed with the unaided eye, and in addition in the tests on the representative samples nearly all specimens were also observed with a 20-power Brinell microscope. The microscope was mounted at the proper angle for observing the crazing and so as to permit vertical movement (see fig. 5). Observations of the extent and nature of crazing were made several times on the first day the load was applied, then generally daily through the fifth day, and once on the eighth day, after which the load was removed. The extent of the crazing from the minimum cross section was measured with a paper scale to the nearest millimeter; this corresponds to an accuracy of better than 1 percent when converted to stress. The observed data on the extent of the crazing were converted into stress values and the latter were plotted against logarithmic time.

Specimens tested at 50-percent relative humidity were conditioned at that humidity at least 2 weeks prior to testing while those tested at 95-percent relative humidity were conditioned 1 week at the latter humidity before testing; the test temperature was 23° C.

Accelerated Weathering Test

The accelerated weathering test employed was the sun-lamp and fog-chamber type. This test was made in accordance with Method No. 6021, Federal Specification L-P-406a, except that it was carried out for 480 hours instead of 240 hours, the recommended time.

Light transmission and haze measurements were taken before and after the weathering test using a Gardner pivotable-sphere hazemeter, following the procedure in A.S.T.M. Method No. D1003-49T.

To permit the measurement of shrinkage, scratches were ruled on each specimen about 2 inches apart before the weathering. The scratches were measured with a steel rule graduated to hundredths of an inch. In measuring the distance between scratches a 7-power magnifier was used, the distance being estimated to 0.001 inch.

Degree of Forming of Representative Samples

Exploratory tests were made with pieces of acrylic plastic sheet biaxially stretched slightly, 7- to 20-percent elongation, and moderately, about 45 percent. The latter elongation is an amount that may be attained at some locations in formed aircraft enclosures (references 4 and 5).[2] The results of tensile and stress-solvent-crazing tests indicated that the crazing properties, such as threshold of stress crazing in the standard tensile test and threshold stress for stress-solvent crazing, were unaffected or only very slightly affected by biaxial stretching 7 to 20 percent.[3] However, for the 45-percent-stretched piece, the crazing properties were considerably changed; for example the threshold stress for stress-solvent crazing appeared to increase about 50 percent. Accordingly it was decided to form pieces from each sheet of the representative samples to an elongation of approximately 50 percent.

One piece was formed from each sheet. The piece to be formed was heated in an oven to a temperature of 120° or 140° C, depending on whether the material was general-purpose or heat-resistant grade. Four standard and four tapered tensile specimens and an accelerated-weathering specimen were taken from each disk. An equal number of control specimens were cut out of each sheet from a location adjacent to the piece used for forming.

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[2]In the references mentioned the reduction in thickness was reported, not the elongation; the elongations were calculated using the formula, equation (1).

[3]It was interesting to note that the elongation at failure was increased to the order of about 20 percent by the slight stretching.

While it was desired to obtain the same amount of stretch to within about 5 percent on the three formed pieces of a sample, the actual variation in elongation between disks was greater than this amount except for sample P1a. The values for individual disks, based on the formula, equation (1), are as follows:

NBS sample	Biaxial stretch of three disks (percent)
L1d	48, 56, 57
L2d	49, 54, 69
P1a	57, 58, 61
P2a	44, 50, 56

RESULTS AND DISCUSSION

Standard Tensile Tests

Results.- The results of the standard tensile tests on the formed and the unformed portions of the four representative samples are shown in table I. Figure 6 illustrates the appearance of the fractures on broken specimens of formed and unformed material.

The tensile strength and secant modulus of elasticity of the four samples of polymethyl methacrylate were unaffected by stretch-forming to about 50-percent elongation. The elongation at failure, as in the exploratory tests, was greatly increased by forming, from approximately 10 percent to about 60 percent. The values for specimens which failed at a strain-gage knife edge or knife-edge mark are noted in table I although most of these values are consistent with the other values.

The strain at the threshold of crazing also was increased greatly as a result of the forming. In fact, for samples L2d, P1a, and P2a, at least half of the specimens showed no stress crazing up to rupture. Crazing on other specimens was very light or was observed only at accidental finger marks.

Discussion of fracture behavior.- It is of interest to consider the fracture behavior and the fracture mechanism in the formed and unformed material. First it was noted that, while the specimens of the unformed material commonly failed at 5- to 10-percent elongation with the fracture approximately flat and normal to the tensile load, as shown by A in figure 6, occasionally a specimen exhibited a much greater elongation, sometimes accompanied by an oblique fracture (B in fig. 6).

Next, it was observed that the formed specimens as shown in figure 6 (C, D, E, and F) had a laminar fracture. The laminar fracture of formed material indicates that the segments of the polymer molecules have a preferred orientation in the plane of the sheet thus favoring fracture propagation on planes nearly parallel to the plane of the sheet. In the unformed material the segments of the polymer molecule are assumed to be randomly oriented.

Although it is not readily seen from figure 6, on the fracture surface of each specimen there was a small mirrorlike area oriented perpendicularly to the tensile load. On specimens of unformed material the mirror area was diffusely bounded; on the formed the boundary was sharp. The mirrorlike area was of the order of a millimeter in dimensions and was always found extending in from the edge of the cross section.

On unformed material this area was located at the corner of the cross section for most of the specimens; in the other instances it was found either extending inward from the cast edge or from the machined edge. At corner locations the mirror was roughly a quadrant of a circle and at edges it was semicircular.

On specimens of formed material the mirror area was located at a corner on almost all of the specimens; however, on the other specimens the mirrors were located only at the machined edge. At corner locations the mirror area was almost a right triangle, with the hypotenuse a convex curve instead of a straight line; the area extended much farther along the cast edge than along the machined edge. When located on a machined edge the mirror area appeared to be somewhat less than a semiellipse with the major axis normal to the edge. In testing a formed specimen usually some edge cracks appeared normal to the edge after the material had been strained considerably. These cracks became larger as the specimen was stretched further, and at failure the fracture appeared to go through one of them. In figure 6 two such cracks are evident on the left edge of specimen C just above the identifying letter. Such cracks reflect light similarly to large crazing cracks, indicating a mirrorlike surface. Also, the large edge cracks extend farther in the direction of the cast surface than in the thickness direction as in the case of the mirror areas on the fracture surface.

For this reason it is quite plausible to expect the fracture in specimens of the formed material to start at such edge cracks.[4]

From the fracture behavior of specimens of unformed material, discussed below, it is logical to suppose that the fracture in such material also begins in the mirror area and that in this material this area is an extension of a crazing crack.

The experimental evidence which suggested that the fracture started at the mirror area is as follows: The fractures were examined on a large number of unformed tensile specimens which were solvent-crazed and then broken. The tensile tests were done in connection with another phase of this investigation on crazing (reference 6). The specimens, of the standard tensile type, were wetted with benzene while under a load; the solvent was applied to the central 1/4- by 2-inch portion of one face of the reduced part of the specimen. On all the specimens inspected it was noted that a semicircular mirrorlike area was present on the fracture surface; this area was located with its center at or near the solvent-crazed surface. It is plausible to suppose that this mirror area is an extension of a solvent craze crack, and hence that fracture is initiated at such a crack. This hypothesis was strengthened by comparing the location of the fractures on a number of these specimens with photographs of the solvent-crazed specimens taken prior to breaking. In all cases, the fracture was found to pass through a crazing crack. Visual evidence to justify further this supposition was obtained in a different portion of the investigation, the results of which are as yet unpublished. In this work, experiments were made on several different cast polymethyl-methacrylate sheets of viscosity average molecular weights ranging from 90,000 to 3,000,000. In stress-solvent crazing tests on low-molecular-weight material, one or a few large crazing cracks developed, and the specimens were seen to fail by the rapid growth of one craze crack. It should be noted that solvent crazing reduces the tensile strength of the specimens (reference 6).

Since the evidence on the solvent-crazed specimens strongly suggests fracture propagating outward from the mirror area which originates at a crazing crack, and since similar mirror areas extending in from the edge are found in standard tensile specimens that are not solvent-crazed, it seems reasonable to conclude, as previously noted, that failure begins at the surface of the specimen and the mechanisms of fracture and crazing are closely related. Indeed, one might go further and say that in the specimens of unformed material that are not solvent-crazed the fracture first starts at a stress-crazing crack. In the

[4]In this report these edge cracks have somewhat arbitrarily been considered as distinct from crazing cracks; also any fine crazing on machined edges was disregarded. The reason is that such edge cracks and crazing are dependent on the machining of the specimens and could possibly be minimized or caused to begin at higher strains by varying the machining technique or by properly annealing the specimens.

formed specimens, which frequently do not exhibit stress crazing, the fracture of the specimens is delayed, that is, occurs at a much higher strain than in the unformed material. Furthermore, the true stress is probably higher at or near failure in the formed material than in the unformed as was actually found in a few tests.[5]

The difference in appearance between the mirror part of the fracture surface and the rougher portion may be associated with a low velocity of fracture propagation at the former and a higher velocity in the rougher portion. Such an explanation of the fracture behavior of glass is discussed by Morey (reference 7) in his monograph on glass.

The fact that on the broken specimens of formed material the mirror area had a smaller dimension in the direction perpendicular to rather than parallel to the plane of the sheet or laminae suggests that the rate of crack growth, and perhaps the subsequent high-speed fracture too, is slower across the laminae than parallel to them.

Hsiao and Sauer (reference 8), who studied crazing in specimens of polystyrene, present a different picture of the relation between crazing and fracture. They conclude that the fracture cracks of the material are not the same as crazing cracks and that the source of fracture is usually some flaw in the material and not one of the crazing openings. However, it would seem reasonable to expect that, since the crazing crack produces a stress concentration at its apex, the subsequent fracture would be initiated at the apex of the crack. A microscopic examination of the fracture surfaces, such as carried out by Kies and his coworkers (reference 9) on several materials, would possibly clarify the situation.

Stress-Solvent Crazing Tests

The threshold stress data for the stress-solvent crazing tests on the disks which were 50-percent biaxially stretched are shown in table II. Typical specimens of all samples are shown in figures 7 through 10. The threshold was determined visually using two criteria. For the first, called criterion A, the threshold was taken as the maximum

[5]In the exploratory work with specimens of a disk biaxially stretched to 45-percent elongation, the load-elongation graph was taken out to 50-percent strain with a low-magnification recording strain gage. After the maximum load was attained, at about 4-percent strain, the load declined with increasing strain to about four-fifths of its maximum value and then remained almost constant out to 50-percent strain, the limit of elongation of the strain gage; at this point the load was increasing slowly. Since the volume of the material remains practically constant in the plastic range, the reduced cross-sectional area can be calculated from the strain and the true stress then derived. It was found that the true stress at 50-percent strain was about 10 percent greater than at the maximum load.

stress below which there was no regular distribution of crazing cracks visible to the unaided eye, the isolated cracks being disregarded; this was the same criterion as was used in the exploratory tests. For the second, criterion B, the threshold stress was taken as the maximum stress below which no crazing cracks were visible to the unaided eye.

As might be expected, the average threshold crazing stress obtained by criterion B was slightly less than by criterion A. The principal results as obtained by the two methods were in agreement, however, and are as follows:

The average threshold crazing stress for general-purpose-grade polymethyl methacrylate, crazed with benzene by the procedure described previously, was about 2000 psi for unformed and about 3400 to 3800 psi for the sheets which were 50-percent biaxially stretched. The corresponding values for the heat-resistant grade were about 3000 psi and 5000 to 6000 psi, respectively. This represents an improvement of from 70 to 80 percent for each grade.

Not only did the formed specimens exhibit higher threshold stresses than the unformed but also there was a tendency for the crazing cracks to be somewhat finer and more closely spaced on the formed specimens. This effect of forming is illustrated in figures 7, 8, and 10, for samples L1d, P1a, and P2a, respectively.

Long-Time Tensile Tests

Threshold-stress-crazing data.- Values of threshold stress for stress crazing at 1, 10, and 100 hours, derived from plots of threshold stress against logarithmic time, are given in table III.

The plots of threshold crazing stress against logarithmic time were in general approximately linear. One of these plots is shown in figure 11 to illustrate the type of graph obtained from the data. For most specimens the extent of crazing was recorded separately for each face of the specimen, as the crazing often progressed more rapidly on one face than on the other. An examination of the plotted data showed no consistent behavior of the masked relative to the unmasked face.[6] Any consistent difference in the extent of crazing on the two faces was accordingly assumed to be caused by a slight misalinement of the specimen. In such cases, a single straight line was fitted by eye to the data for the two faces and the values in table III were taken from this line.

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[6]In experiments described in reference 6, in which loss of strength was determined as a result of stress-solvent crazing, no effect of masking paper was detected.

The slopes of the plots of threshold stress against logarithmic time appeared to be about the same for all materials and test conditions. The effect on the threshold stress of factors such as forming, relative humidity, sample, and grade is indicated best by examining the 100-hour unaided-eye values, as these are the most numerous and precise. These values, taken from table III, together with values of the ratio of the threshold stresses for the formed and unformed specimens of each sample are listed below:

NBS sample	σ_c at 50-percent relative humidity (psi) (a)		$\frac{\sigma_{c,F}}{\sigma_{c,U}}$	σ_c at 95-percent relative humidity (psi) (a)		$\frac{\sigma_{c,F}}{\sigma_{c,U}}$
	Formed, F	Unformed, U		Formed, F	Unformed, U	
L1d	3750	2450	1.53	3350	<2500	>1.34
P1a	>4000	3050	>1.31	>4000	2850	>1.40
L2d	5500	3300	1.67	[b]5000	3400	1.47
P2a	5750	4000	1.44	5650	4150	1.36

[a]Average for two specimens.
[b]Value for one specimen only.

The standard error of the stress values shown above is of the order of 200 psi, based on the agreement between duplicates. The data listed above indicate that forming to a biaxial strain of about 50 percent increases the threshold crazing stress of all samples about 40 to 50 percent. From table III it is also evident that the threshold stress is about 30 to 50 percent higher for the heat-resistant than for the general-purpose grade. The data are not precise enough to determine with certainty any difference in threshold crazing stress due to relative humidity or to material of a given grade. It will be noticed, however, that the Plexiglas values are consistently higher than those for Lucite of the corresponding grade for both formed and unformed specimens; in all but one instance the difference is at least 10 percent.

Threshold-stress values obtained with the microscope were usually lower than those obtained with the unaided eye as might be expected (see table III). Occasionally the unaided-eye reading was lower than the microscope value. One reason for this is that the angle of tilt of the microscope is an optimum for observing crazing near the minimum section of the specimen; the angular relations of the light source, crazing cracks, and microscope are changed enough near the maximum cross section to make tiny cracks less easily detected at this location. Also with the unaided eye it was frequently difficult to distinguish the very fine crazing from dust on the specimens.

Appearance of specimens.- The appearance of the long-time tensile-loading specimens is illustrated by photographs of each set of specimens taken near the end of the testing period (figs. 12 through 16). The specimens were photographed while under load as the finest crazing cracks usually disappear on removal of the load as noted by other workers. Two photographs were taken consecutively of the set of specimens of sample L1d with different exposure times. This enables one to see the finer type of crazing in the longer exposure (fig. 12) and to see the heavier crazing in the shorter exposure (fig. 13) without its being overexposed.

The threshold-crazing-stress values give an incomplete picture of the effect of forming and other variables on the crazing behavior of the materials. Thus, the crazing on the formed specimens, where it occurs, is usually finer than that on the unformed specimens. This can be seen from the photographs, figures 12 to 16, and is even more evident from a visual inspection of the specimens themselves. Also, although the threshold stresses at 95- and 50-percent relative humidity did not differ appreciably in general, the nature of the crazing at the two relative humidities was markedly different. The cracks at 95-percent relative humidity appeared finer and more closely spaced and were almost always noticeably shorter than those at the lower relative humidity (see figs. 13, 14, and 16 especially).

For most specimens the lengths of the longest cracks in the vicinity of the minimum section were measured with the Brinell microscope. A few cracks of exceptional length, appearing to be two or more cracks joined together or to be initiated at very fine, long scratches, were disregarded. The cracks measured on the unformed specimens after 100 hours at 50-percent relative humidity were from 0.4 to 0.7 millimeter long; at 95-percent relative humidity they were in general about 0.1 to 0.3 millimeter long. The formed specimens, in the few instances where the data were available (all on heat-resistant material), had corresponding crack lengths of close to 0.2 millimeter at the 50-percent relative humidity and 0.1 millimeter at the 95-percent relative humidity.

It should be noted that the formed and unformed specimens cannot be compared on the basis of the above crack length data since the cracks on the two sets of specimens had started at different times and the length of a crack apparently depends on the "crack lifetime," that is, the time elapsed under load since the crack appeared. Nevertheless, when the crack lifetime was taken into account the cracks on the unformed specimens seemed to grow more rapidly than on the formed specimens even when the stress was appreciably higher on the latter. For example, on one formed specimen of sample P2a at 50-percent relative humidity, cracks were first observed at the minimum cross section (6000-psi stress) at about 50 hours and, after 50 hours of crack lifetime, the longest cracks in this area were close to 0.15 millimeter in length. On the corresponding unformed specimens with only 5000-psi stress at the minimum cross section the cracks were 0.35 to 0.4 millimeter long for the same crack lifetime. The difference in length is not as noticeable on specimens at 95-percent relative humidity.

Another effect of the high humidity was to increase the rate of creep markedly at the stresses used in the long-time tensile tests. Some of the specimens at the 95-percent relative humidity necked down at the minimum section near the end of the testing period (see figs. 14, 15, and 16). The formed specimens of the heat-resistant materials necked down sooner than the corresponding unformed specimens as can be seen from the figures; however, it should be noted that these formed specimens had a 20-percent-higher stress than the unformed. The necking down of the formed and unformed specimens of samples L1d and P1a at the high humidity was about the same as indicated by figures 12 and 15; the stress at the minimum cross section was the same for all specimens of a sample. Sample P1a is the only one of the four materials on which it was not possible to obtain values of threshold stress for stress crazing at the high relative humidity; at the loads used the material creeps before crazing can begin.

Discussion of Mechanism of Crazing

The effects of biaxial stretch-forming on the crazing behavior of polymethyl methacrylate perhaps may be explained qualitatively on a molecular basis as follows. In the unformed state the polymer molecules are assumed coiled in an approximately spherical shape; the chain segments have no preferred orientation. In the formed state the molecules should be somewhat uncoiled and in a roughly disklike shape with the chain segments oriented predominantly in the plane of the material. The following mechanism of crazing, somewhat similar to that proposed by Maxwell and Rahm (reference 10) is postulated. The crazing is assumed to start at the surface at submicroscopic flaws or weak points. Such weak points may be submicroscopic regions in which by chance the polymer chain segments are oriented normal to the applied tensile stress. With sufficient stress a separation between portions of adjacent chains occurs; a stress concentration exists at the apex of the crack and the latter grows until it reaches a region in which the polymer chain segments are oriented approximately in the direction of the tensile stress. The crack either does not grow or grows slowly unless the tensile stress is greatly increased. Subsequent crack growth may involve rupture of primary valence bonds especially if the stress is relatively high, of the order of the tensile strength.

The process of biaxial stretch-forming, by orienting the chain segments in the plane of the sheet, reduces the proportion and size of the weak normally oriented regions and increases the regions of predominantly parallel orientation. Stated differently the stretch-forming may be said to introduce "cleavage" planes in the plane of the sheet. This orientation or introduction of cleavage planes greatly impedes the development and growth of crazing cracks. Thus, as noted previously in the long-time tensile-loading tests, the crazing cracks, after becoming visible, grew more slowly on formed as compared with the corresponding unformed specimens.

In regard to stress-solvent crazing, mechanisms have been suggested by various authors (references 11, 12, and 13) which while differing in some aspects include as a factor the concept of the solvent acting as a plasticizer. By using this concept the mechanism suggested above for stress crazing may be modified to include the influence of solvents as follows. The solvent molecules penetrating the surface of the polymer tend to surround portions of the polymer chains and reduce the forces required to separate them. Because of this weakening influence of the solvent molecules, at a surface flaw such as a region of normal orientation of the polymer chains, the stress concentration that can be withstood is reduced and a tiny crack develops at a lower applied stress than in the absence of solvent. The solvent molecules by capillarity probably fill the crack as it grows and continue to exert a weakening influence at the apex. In this connection it has been suggested by Hopkins, Baker, and Howard (reference 13) that another weakening influence at the apex of a crack is the film spreading pressure of the crazing liquid.

The effect of forming on stress-solvent crazing might be expected to be similar to that for stress crazing. The reduction in the number and size of the regions of normal orientation and the increase in the regions of parallel orientation should result in higher threshold stresses for the formed material. Also, for formed material as for unformed, the crazing stress should be lower in the presence of than in the absence of solvent owing to the weakening influence of the solvent.

Accelerated Weathering Tests

The results of the 480-hour sun-lamp and fog-chamber accelerated weathering tests are shown in table IV.

The light-transmission values for all the materials, both unformed and formed, are 92.0 ± 0.1 percent initially and 92.3 ± 0.3 percent after weathering. While the transmission values are slightly higher after weathering, the differences, which do not exceed 0.5 percent, are considered within the experimental error of measurements made at different times. The haze values are approximately 0.5 ± 0.2 percent for all materials both formed and unformed and before and after weathering. In this connection, the specimens were inspected visually after the weathering test but no crazing was observed on any of them.

For all samples the shrinkage of the unformed or control specimens was very slight, averaging 0.05 to 0.1 percent; these values are of the order of magnitude of the standard error of the shrinkage values. The formed specimens of the heat-resistant-grade samples shrank only 0.2 percent; however, similar specimens of the general-purpose-grade samples shrank somewhat more, the values being 1 and 2.3 percent for Plexiglas I-A and Lucite HC201, respectively.

Most of the specimens were slightly warped after the weathering test. In general the formed specimens were more warped than the unformed, particularly for the general-purpose-grade materials.

The greater dimensional changes for formed pieces of the general-purpose-grade samples as compared with the heat-resistant grade are not surprising for the following reason. The specimen temperature in the test is about $60^\circ \pm 5^\circ$ C which is not far below the second-order transition temperature of the general-purpose-grade samples, namely, 75° to 80° C; the corresponding temperature for the heat-resistant grade is about 94° to 95° C.[7]

Additional Experimental Work

Verification of the results obtained in this laboratory by other experimenters is desirable. Some experiments toward this end have been made at the Lockheed Aircraft Corporation on specimens from two biaxially stretched disks furnished by this laboratory (reference 14). The Lockheed results, based on the few specimens available, agree generally with those obtained at this laboratory. It was found that stretch-forming increased the elongation at failure and increased the resistance to stress-solvent crazing with acetone and isopropyl alcohol, the two liquids used. In addition, in outdoor-weathering-under-load tests at stresses of 2000 and 4000 psi, it was observed that the formed specimens showed greatly improved crazing properties; however, the formed material had a tendency to creep much more than control material.

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[7]These values were derived from volume-temperature measurements made on these samples over the temperature range from 25° to 110° C; a mercury dilatometer was used.

Possible Applications of Stretch-Forming

The improvement in the crazing properties of acrylic plastic sheet produced by moderate (50-percent) biaxial stretch-forming suggests that formed enclosures made from prestretched flat sheets may have superior crazing and strength properties compared with enclosures formed from normal sheets.

Assuming that the technical difficulties of preparing biaxially stretched flat sheets of the desired thickness, size, and optical quality have been overcome, the procedure for preparing a formed enclosure such as an astrodome from a stretched sheet could be as follows. Such a sheet, slightly larger than the blank required for the enclosure, is clamped or bolted near the edge between two stout metal rings. To prevent the sheet from shrinking to its original state the rings are left in place when the sheet is heated prior to forming and when it is clamped to the form or mold. In an astrodome as prepared normally, as for example by vacuum drawing, there is a maximum amount of stretch and craze resistance at the apex and negligible stretch and minimum craze resistance at the rim. The use of prestretched sheet would hence improve the craze resistance especially at the rim where contact with crazing liquids is quite likely.

As an alternative to using prestretched material to achieve improved craze resistance at the edge of acrylic enclosures, there is the possibility of preparing an enclosure larger and more deeply drawn than required and then using only the central portion of the formed piece.

Before investigating these possibilities, however, it is believed desirable to determine first the effects of stretch-forming on other physical properties such as creep, abrasion resistance, natural weathering while under load, impact resistance, fracture under bullet impact, and crazing with various solvents. For both practical and fundamental reasons, the effects of higher degrees of stretching should also be determined.

CONCLUSIONS

Some of the effects on polymethyl methacrylate of biaxial stretch-forming to about 50 percent are as follows:

1. The strain at the onset of crazing in the standard tensile test is greatly increased; in fact, in tests performed, most specimens showed no crazing. The tensile strength and secant modulus of elasticity are

unaffected. The elongation at failure is increased from approximately 10 percent to about 60 percent.

2. The threshold stress for stress-solvent crazing with benzene is increased about 70 to 80 percent for both general-purpose and heat-resistant grades.

3. In long-time tensile tests of up to 7 days' duration: (a) The threshold stress for stress crazing is increased about 40 to 50 percent for both grades of material at both 50- and 95-percent relative humidity; and (b) the crazing cracks produced are somewhat finer and appear to grow in length more slowly.

From these effects it may be concluded that:

1. The effect of biaxial stretch-forming on other physical properties as well as the effects of higher degrees of stretching should be investigated for both practical and fundamental reasons.

2. The considerable increase in the elongation at failure and in the stress-crazing and stress-solvent-crazing threshold of polymethyl methacrylate as a result of moderate (50-percent) stretch-forming suggests that formed enclosures made from prestretched flat sheets may have greatly improved crazing resistance and strength properties, possibly to the extent that acrylic glazing need not be laminated. Any research to develop such enclosures should probably be done with heat-resistant- rather than general-purpose-grade material in view of the superior strength and crazing properties of the former grade.

National Bureau of Standards
Washington, D. C., Oct. 25, 1951.

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TABLE I.- TENSILE PROPERTIES OF POLYMETHYL METHACRYLATE FORMED BY BIAXIAL STRETCHING[a]

Material	NBS sample	Biaxial stretch (percent) (b)	Tensile strength, σ_{max} (psi)	Total elongation (percent)	Secant modulus (psi) (c)	Stress and strain at threshold of crazing: Stress, σ_c (psi)	$\frac{\sigma_c}{\sigma_{max}}$	Strain (percent)
Unformed:								
Lucite HC201	L1d	--	7850 ± 80	[d]8.8 ± 1.2	3.63 ± 0.05 × 10^5	6780 ± 140	0.86	2.4 ± 0.15
Lucite HC202	L2d	--	9580 ± 100	14 ± 3	4.00 ± 0.03	8380 ± 180	.88	2.9 ± 0.3
Plexiglas I-A	P1a	--	7920 ± 50	19 ± 7	3.75 ± 0.01	7170 ± 100	.91	2.6 ± 0.1
Plexiglas II	P2a	--	10070 ± 170	[e]7.6 ± 0.4	4.06 ± 0.09	9080 ± 180	.90	3.2 ± 0.1
Formed:								
Lucite HC201	L1d	54	7830 ± 130	[f]73 ± 3	3.60 ± 0.05	----------	----	Very light crazing, two specimens crazed at 4 and 6.5 percent, others at hand marks at >10-percent strain
Lucite HC202	L2d	57	9650 ± 140	59 ± 4	4.01 ± 0.05	----------	----	Three specimens did not craze; very light crazing on two specimens at ≈7 percent on one at >10-percent strain
Plexiglas I-A	P1a	59	8030 ± 90	67 ± 4	3.73 ± 0.05	----------	----	Four specimens did not craze; possible very faint crazing on two specimens
Plexiglas II	P2a	50	9930 ± 80	49 ± 3	4.04 ± 0.01	----------	----	Three specimens did not craze; very light crazing on others at hand marks at >10-percent strain

[a]Tests were made on standard tensile specimens, Federal Specification L-P-406a, Method No. 1011, Type I. Testing speed was 0.05 in./min up to 10-percent elongation; strain gage was removed at this point and speed increased to 0.25 in./min with further elongation measured with dividers. Testing was done at 23° C and 50-percent relative humidity. All results are the average for six specimens, two specimens from each sheet, unless otherwise noted, plus or minus the standard error. Standard error was calculated taking into account possible existence of sheet-to-sheet variations.

[b]Average for three disks.

[c]Stress range used for calculation of secant modulus was 0 to 4000 psi for Lucite HC201 and Plexiglas I-A and 0 to 5000 psi for Lucite HC202 and Plexiglas II.

[d]One specimen failed at knife edge, at 5.1-percent elongation.

[e]Two specimens failed at knife edges, at 4.4- and 9-percent elongation.

[f]Two specimens failed at knife-edge marks, each at 77-percent elongation.

TABLE II.- THRESHOLD CRAZING STRESSES FOR STRESS-SOLVENT-CRAZED SPECIMENS OF POLYMETHYL METHACRYLATE FORMED BY BIAXIAL STRETCHING[a]

NBS sample	Material	Biaxial stretch (percent) (b)	Threshold crazing stress, σ_{sc} (c)		Range of σ_o, maximum stress applied, for set of specimens (psi)
			Criterion A (psi) (d)	Criterion B (psi) (d)	
	Unformed:				
L1d	Lucite HC201	--	2110 ± 40	2000 ± 50	2700 - 3000
L2d	Lucite HC202	--	[e]>3020 ± 40	[e]>2820 ± 190	3000 - 3600
P1a	Plexiglas I-A	--	2300 ± 150	2120 ± 120	2400 - 3000
P2a	Plexiglas II	--	3270 ± 140	3120 ± 160	3900 - 4500
	Formed:				
L1d	Lucite HC201	54	[f]>3390 ± 150	[f]>3310 ± 130	3000 - 4500
L2d	Lucite HC202	57	[e]>5550 ± 280	[e]>5130 ± 380	5600 - 6900
P1a	Plexiglas I-A	59	3890 ± 310	3690 ± 310	4200 - 5400
P2a	Plexiglas II	50	[e]>5720 ± 90	[e]>5590 ± 110	6000 - 7200

[a]A controlled amount of benzene was applied to a camel's hair brush; then central 1/4- by 3-in. portion of one face of tapered tensile specimen, which was under load, was stroked with brush. Specimens were under load for 4 min and then were removed from testing machine; after 4 to 6 days they were examined for crazing thresholds. Crazing was done in a controlled-atmosphere room operating at temperature of 23° C and 50-percent relative humidity.

[b]Average for three formed disks, one from each sheet of sample.

[c]Each value is average plus or minus standard error for six specimens with two specimens from each sheet. Standard error was calculated taking into account possible existence of sheet-to-sheet variation.

[d]Criterion A: Point below which there is no regular distribution of crazing cracks visible with unaided eye; isolated cracks are disregarded. Criterion B: Point below which no crazing cracks were visible to unaided eye.

[e]One specimen did not craze under load applied.

[f]Two specimens did not craze under loads applied.

TABLE III.- VARIATION WITH TIME OF THRESHOLD STRESS FOR STRESS CRAZING POLYMETHYL METHACRYLATE FORMED BY BIAXIAL STRETCHING[a]

NBS sample	Treatment (b)	Sheet	Biaxial stretch (percent)	Stress range in reduced section of specimen (psi)	Threshold stress (psi) for - (c)											
					50-percent relative humidity after - (d)						95-percent relative humidity after - (d)					
					1 hr		10 hr		100 hr		1 hr		10 hr		100 hr	
					Unaided eye	Microscope (e)	Unaided eye	Microscope (e)	Unaided eye	Microscope (e)	Unaided eye	Microscope (e)	Unaided eye	Microscope (e)	Unaided eye	Microscope (e)
L1d	F	1	48	3750 - 2500	>3750	---	>3750	---	3700	---	>3750	---	3500	---	3800	---
		2	56		>3750	---	>3750	---	[f]3800	---	>3750	---	>3750	---	3500	---
		Average			>3750	---	>3750	---	3750	---	>3750	---	>3620	---	3350	---
	U	1	--	3750 - 2500	3700	---	3000	---	[f]2300	---	---	2800	[f,g]2600	---	<2500	---
		2	--		[f]3900	---	3200	---	2600	---	[f]3100	---	2800	---	2500	---
		Average			3800	---	3100	---	2450	---	---	---	2700	---	<2500	---
L2d	F	1	49	6000 - 4000	>6000	>6000	[f]5900	[f]6000	5100	5100	---	---	---	---	---	---
		3	54		>6000	>6000	[g]6000	[g]6000	[g]5900	[g]5900	>6000	>6000	[f]6200	[f]>6000	5000	5100
		Average			>6000	>6000	6000	6000	5500	5500	---	---	---	---	---	---
	U	1	---	5000 - 3330	[g]4000	---	[g]3500	---	[g]3200	<3300	[g]5000	---	3800	3800	3300	3500
		3	---		[f]5000	---	4200	---	3400	3500	---	---	4300	---	3500	---
		Average			4500	---	3850	---	3300	<3400	---	---	4050	---	3400	---
F1a	F	1	57	4000 - 2670	>4000	>4000	>4000	>4000	>4000	>4000	>4000	>4000	>4000	>4000	>4000	>4000
		2	61		>4000	>4000	>4000	>4000	>4000	>4000	>4000	>4000	>4000	>4000	>4000	>4000
		Average			>4000	>4000	>4000	>4000	>4000	>4000	>4000	>4000	>4000	>4000	>4000	>4000
	U	1	---	4000 - 2670	>4000	>4000	3900	3500	2800	2800	[f]4400	[f]4400	3600	3600	2800	2800
		2	---		>4000	>4000	3800	3900	3300	3200	>4000	>4000	[f]3800	[f]4000	2900	2900
		Average			>4000	>4000	3850	3700	3050	3000	>4200	>4200	3700	3800	2850	2850
F2a	F	1	44	6000 - 4000	>6000	>6000	>6000	>6000	5700	5900	>6000	6000	[f]>6000	[f]>6000	5300	5900
		2	50		>6000	>6000	>6000	>6000	5800	5800	>6000	>6000	>6000	>6000	6000	[g]6000
		Average			>6000	>6000	>6000	>6000	5750	5650	>6000	>6000	>6000	>6000	5650	5650
	U	1	---	5000 - 3330	---	[f]4500	---	4000	3900	3500	>5000	>5000	4700	[f]4600	4300	4100
		2	---		[f]5300	>5000	4700	4600	4100	4000	>5000	>5000	4600	4400	4000	4000
		Average			---	>4750	---	4300	4000	3750	>5000	>5000	4650	4500	4150	4050

[a]Data obtained visually on tensile specimens having reduced section about 3 in. long and tapering uniformly in width from 0.33 to 0.50 in. Specimens were subjected to dead loading in a long-time loading apparatus. Tests were made at 23° C.

[b]Code for treatment: F, formed; U, unformed.

[c]Values are for individual specimens.

[d]Specimens tested at 50-percent relative humidity were conditioned at 50-percent relative humidity for at least 2 weeks prior to testing. Specimens tested at 95-percent relative humidity were conditioned at 95-percent relative humidity for 1 week prior to testing.

[e]A 20-power Brinell microscope was used.

[f]Values were extrapolated.

[g]Values are approximate.

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TABLE IV.- RESULTS OF ACCELERATED WEATHERING TESTS ON POLYMETHYL METHACRYLATE FORMED BY BIAXIAL STRETCHING[1]

NBS sample	Treatment (2)	Light transmission (percent) (3)				Haze (percent) (3)				Shrinkage (percent) (4)		Average warpage (5)
		Initial		After 480 hr		Initial		After 480 hr				
		Average	Range	Average	Range	Average	Range	Average	Range	Average	Range	
L1d	F	92.0	91.9 - 92.1	92.3	92.2 - 92.4	0.7	0.3 - 0.9	0.7	0.5 - 0.8	2.3	1.0 - 4.3	3
	U	92.0	92.0 - 92.1	92.1	92.0 - 92.3	.4	.3 - 0.5	.3	.2 - 0.3	.1	0 - 0.2	1
L2d	F	92.1	92.1 - 92.2	92.6	92.5 - 92.6	0.4	0.3 - 0.5	0.4	0.3 - 0.7	0.2	0.1 - 0.2	1
	U	91.9	91.9 - 91.9	92.1	91.7 - 92.5	.4	.4 - 0.4	.4	.2 - 0.5	.02	0 - 0.05	1
P1a	F	92.1	92.0 - 92.2	92.6	92.5 - 92.6	0.5	0.4 - 0.5	0.3	0.2 - 0.4	1.0	0.6 - 2.0	2
	U	92.0	91.9 - 92.1	92.5	92.5 - 92.6	.4	.4 - 0.5	.4	.3 - 0.5	.05	0 - 0.1	0
P2a	F	92.1	92.1 - 92.1	92.5	92.5 - 92.5	0.4	0.4 - 0.5	0.5	0.3 - 0.7	0.2	0.1 - 0.4	1
	U	92.1	92.1 - 92.2	92.5	92.4 - 92.5	.4	.3 - 0.5	.3	.2 - 0.3	.05	0 - 0.1	1

[1]Amount of stretching in forming was 50 to 60 percent; actual averages for each material are given in table III. Weathering tests were made according to Method No. 6021 of Federal Specification L-P-406a except that testing time was 480 hr instead of 240 hr. Each average is for three specimens, one from each of three sheets of each material.

[2]Code for treatment: F, formed; U, unformed.

[3]Light transmission and haze measurements were made with a pivotable-sphere hazemeter, according to A.S.T.M. Method No. D1003-49T, Procedure A.

[4]Distance between gage marks approximately 2 in. apart was measured before and after test with a steel scale and magnifying glass.

[5]Warpage was classified arbitrarily as follows: 0, none; 1, slight; 2, some; 3, considerable.

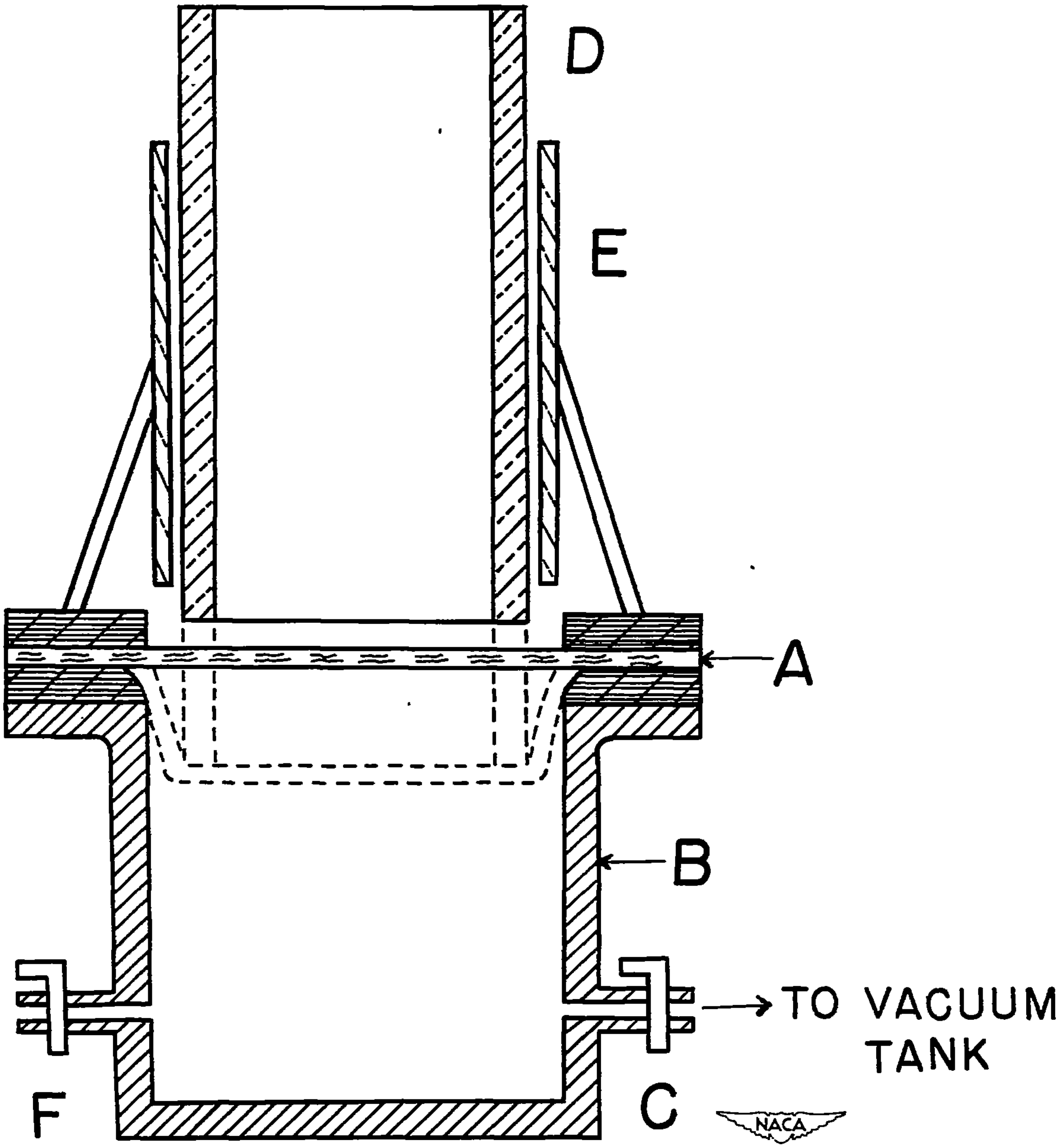

Figure 1.- Schematic drawing of vacuum forming apparatus.
A, plastic sheet to be formed; B, forming vessel; C, valve
to evacuated tank; D, form; E, guide; F, valve to atmosphere.

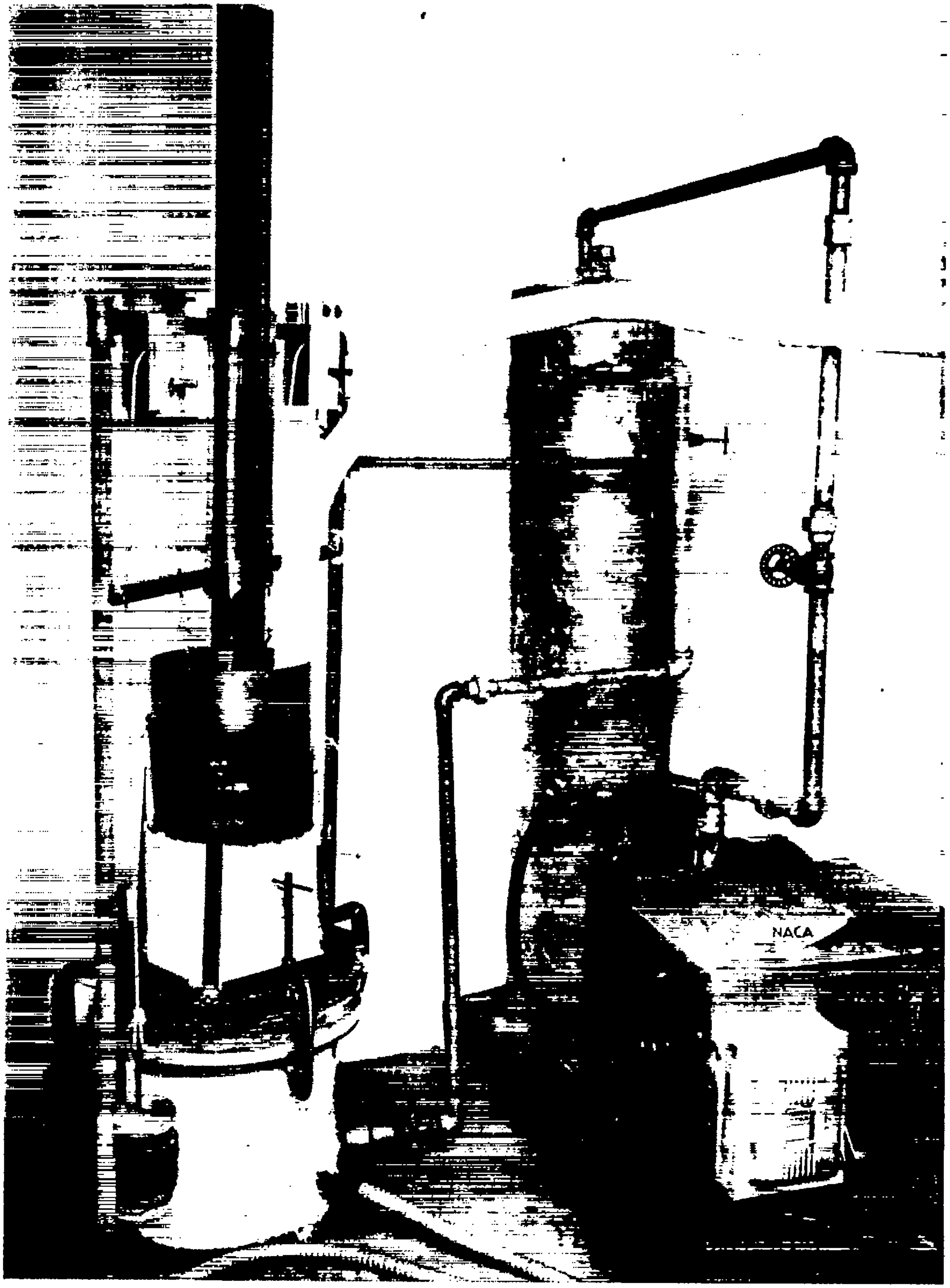

Figure 2.- Vacuum forming apparatus with sheet of acrylic plastic in place ready to be formed.

Figure 3.- Vacuum forming apparatus partly disassembled after forming a sheet of acrylic plastic. Formed piece is on end of form which is held by operator.

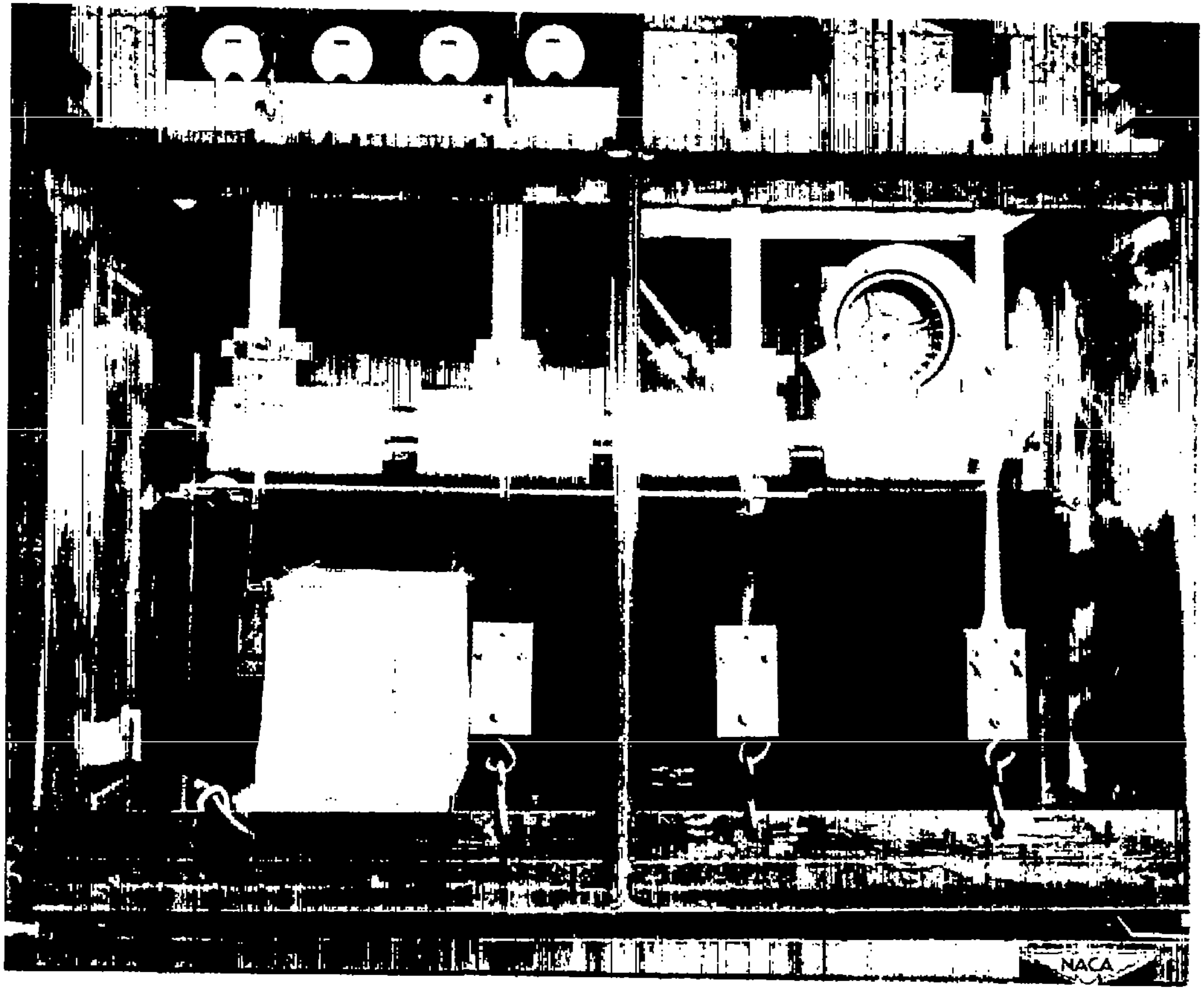

Figure 4.- Interior of long-time tensile-loading cabinet used for testing at high relative humidity.

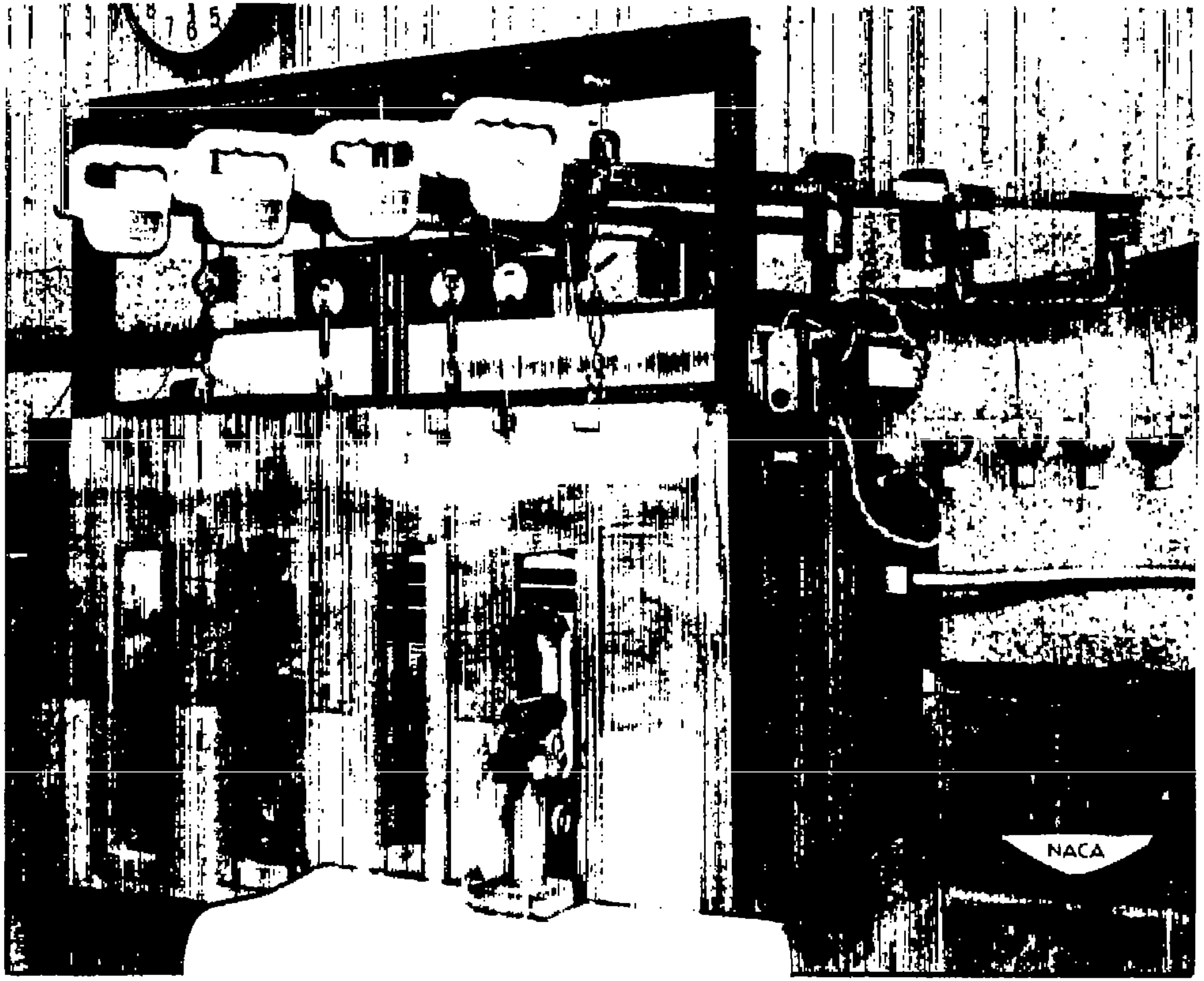

Figure 5.- Exterior of long-time tensile-loading cabinet for testing at high relative humidity. Front of cabinet is in place and Brinell microscope on adjustable stand is inserted in right-hand window for examining crazing of specimen.

Figure 6.- Effect of biaxial stretch-forming to about 50-percent elongation on fracture of tensile specimens.

A: Sample P2a, not formed, 6-percent total elongation
B: Sample Pla, not formed, 54-percent total elongation
C: Sample Lld, 57-percent formed, 77-percent total elongation
D: Sample Pla, 58-percent formed, 57-percent total elongation
E: Sample L2d, 49-percent formed, 52-percent total elongation
F: Sample P2a, 55-percent formed, 40-percent total elongation

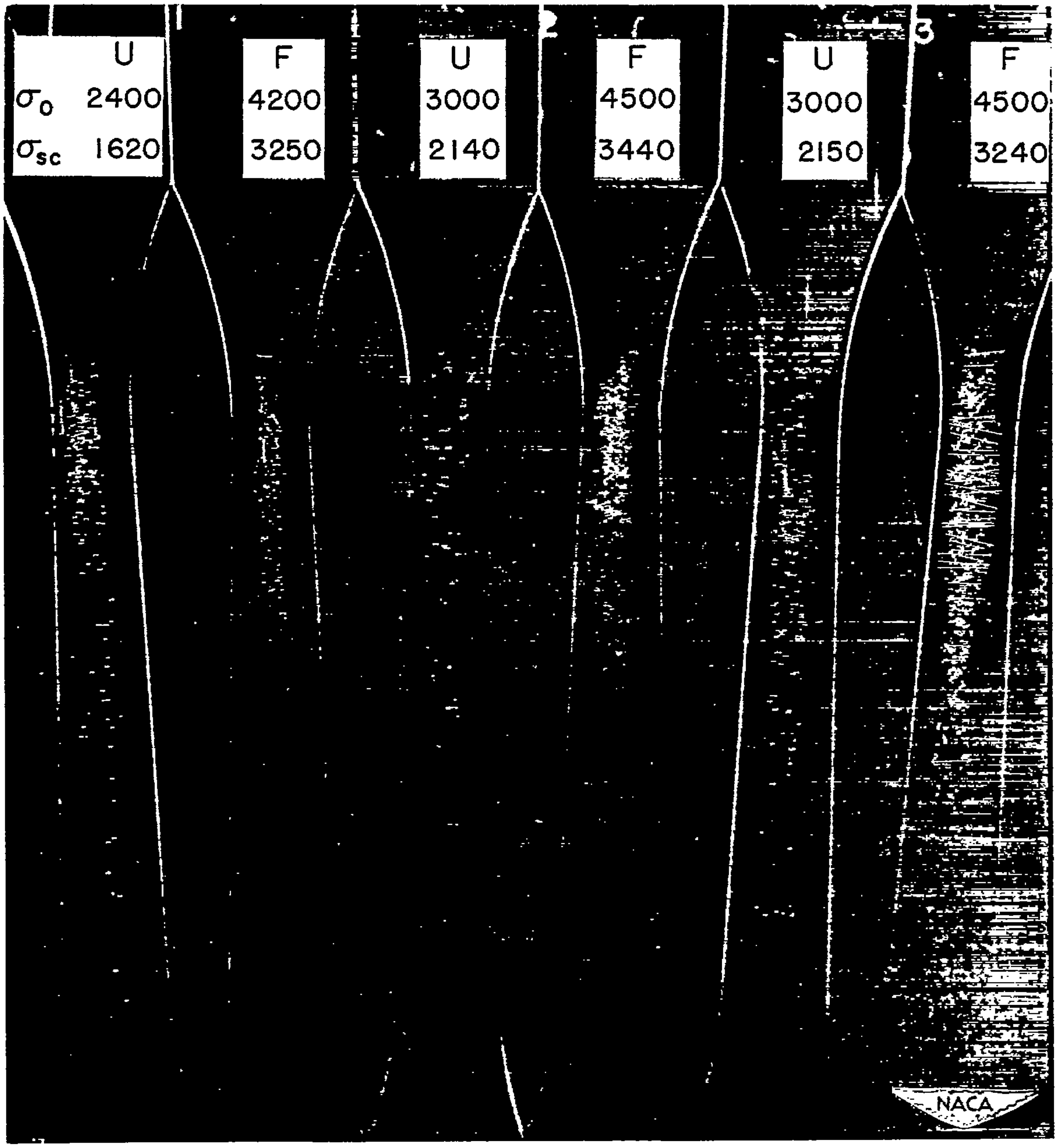

Figure 7.- Specimens of formed and of unformed portions of sample L1d after stress-solvent crazing with benzene. Number on top line designates sheet from which specimen was taken. Letter designations are: U, unformed material; F, formed material; σ_o, stress in pounds per square inch at minimum cross section of specimen; σ_{sc}, threshold crazing stress according to criterion B.

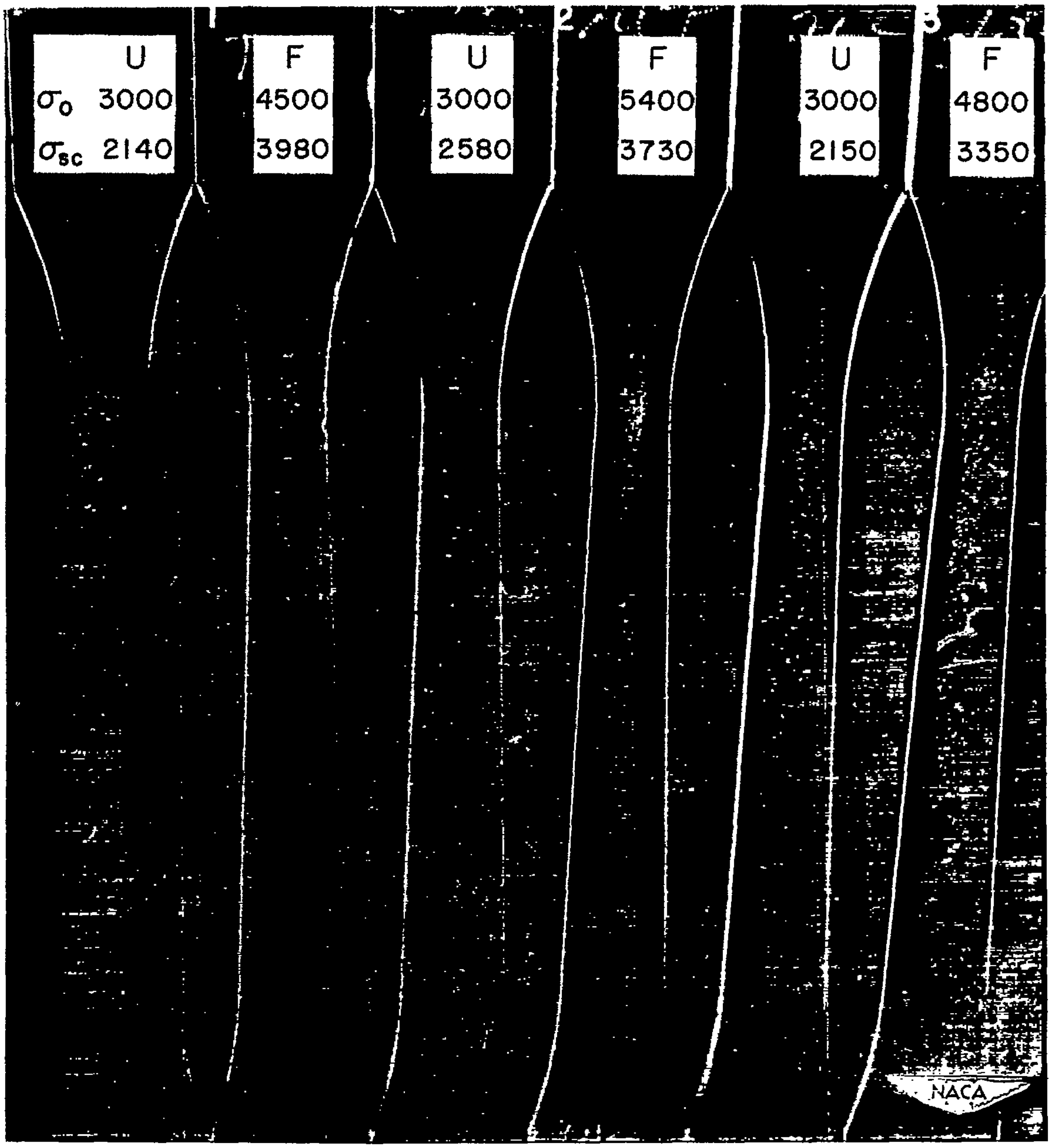

Figure 8.- Specimens of formed and of unformed portions of sample P1a after stress-solvent crazing with benzene. Number on top line designates sheet from which specimen was taken. Letter designations are: U, unformed materials; F, formed material; σ_O, stress in pounds per square inch at minimum cross section of specimen; σ_{SC}, threshold crazing stress according to criterion B.

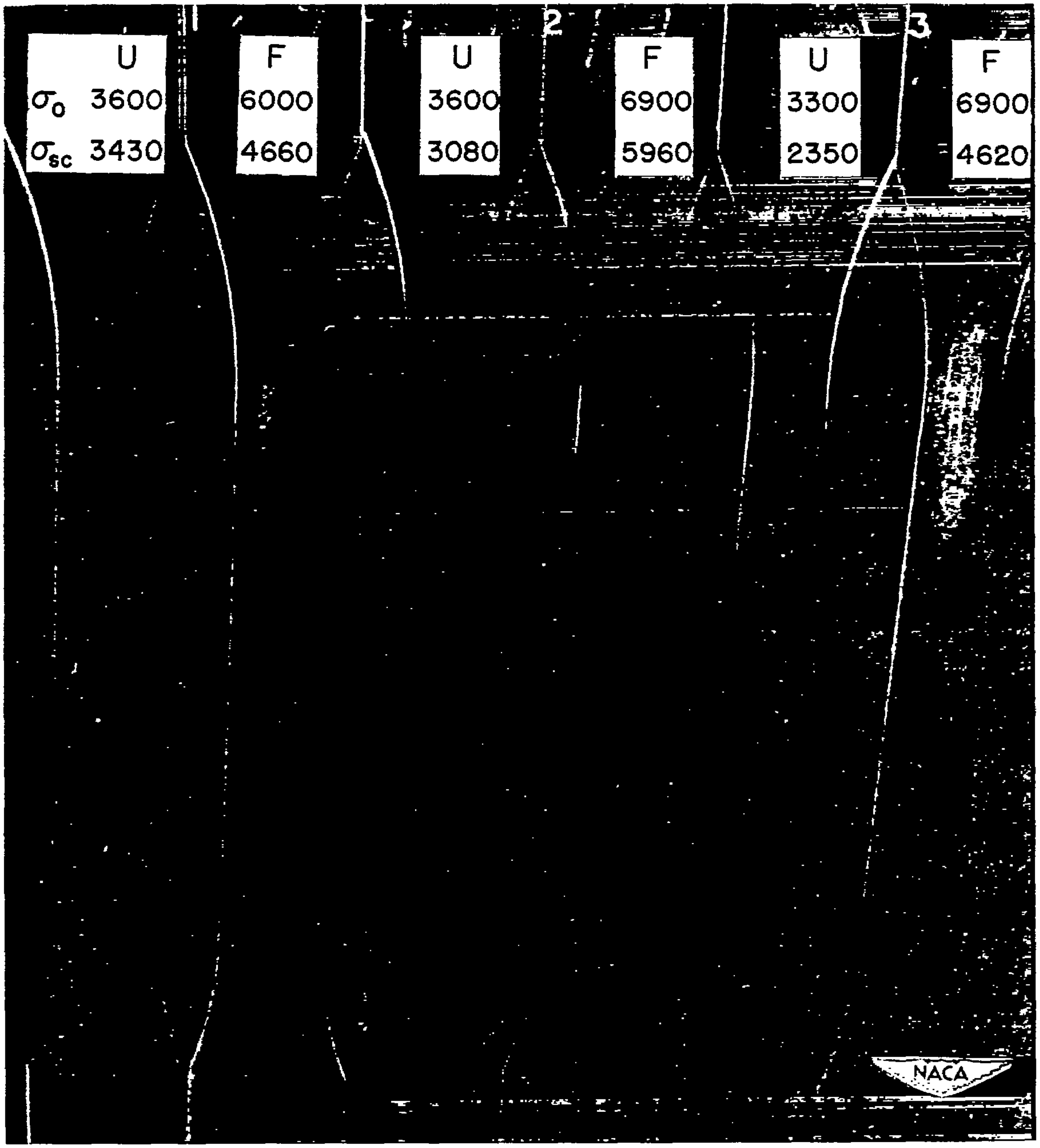

Figure 9.- Specimens of formed and of unformed portions of sample L2d after stress-solvent crazing with benzene. Number on top line designates sheet from which specimen was taken. Letter designations are: U, unformed material; F, formed material; σ_0, stress in pounds per square inch at minimum cross section of specimen; σ_{sc}, threshold crazing stress according to criterion B.

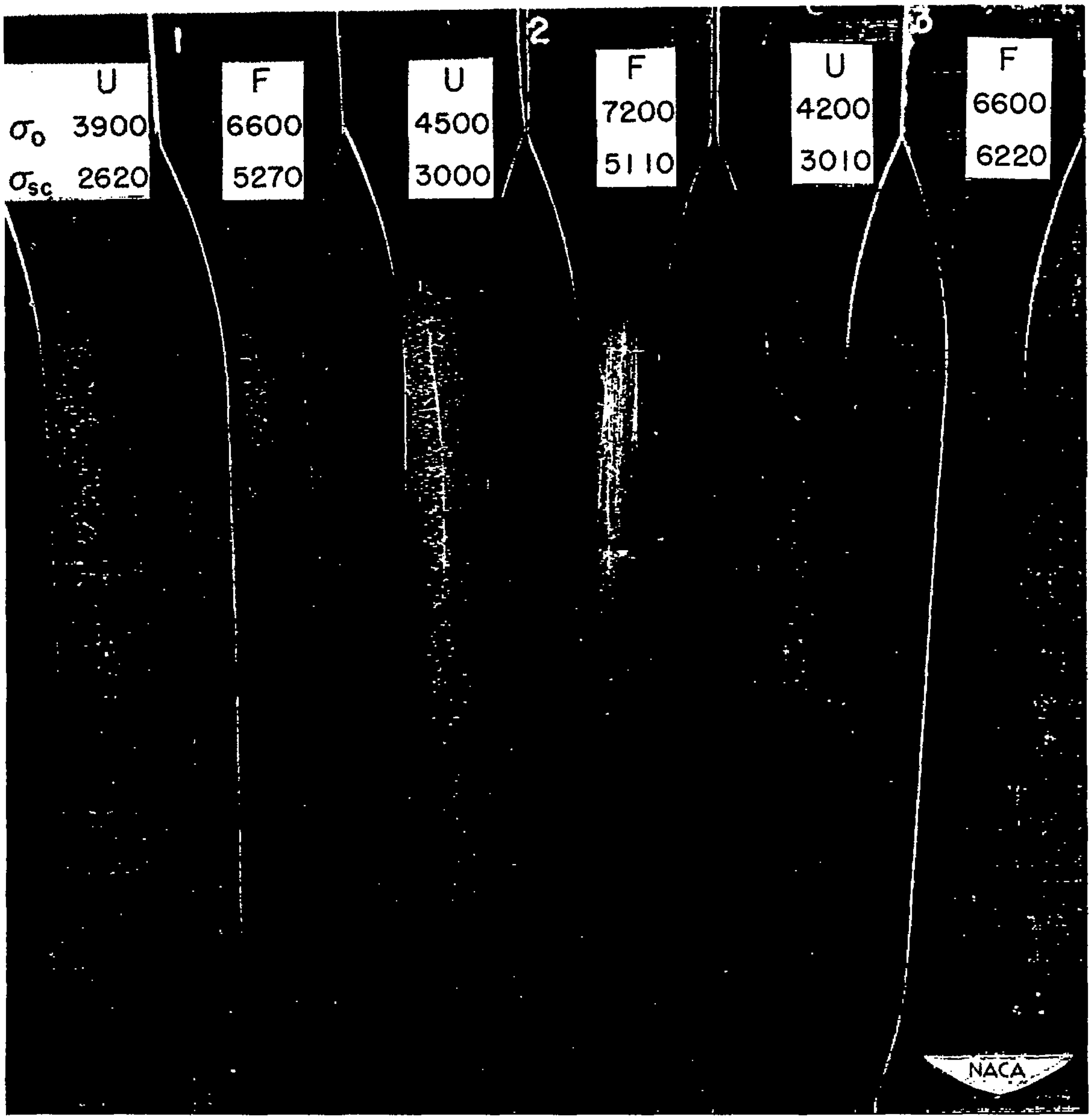

Figure 10.- Specimens of formed and of unformed portions of sample P2a after stress-solvent crazing with benzene. Number on top line designates sheet from which specimen was taken. Letter designations are: U, unformed material; F, formed material; σ_o, stress in pounds per square inch at minimum cross section of specimen; σ_{sc}, threshold crazing stress according to criterion B.

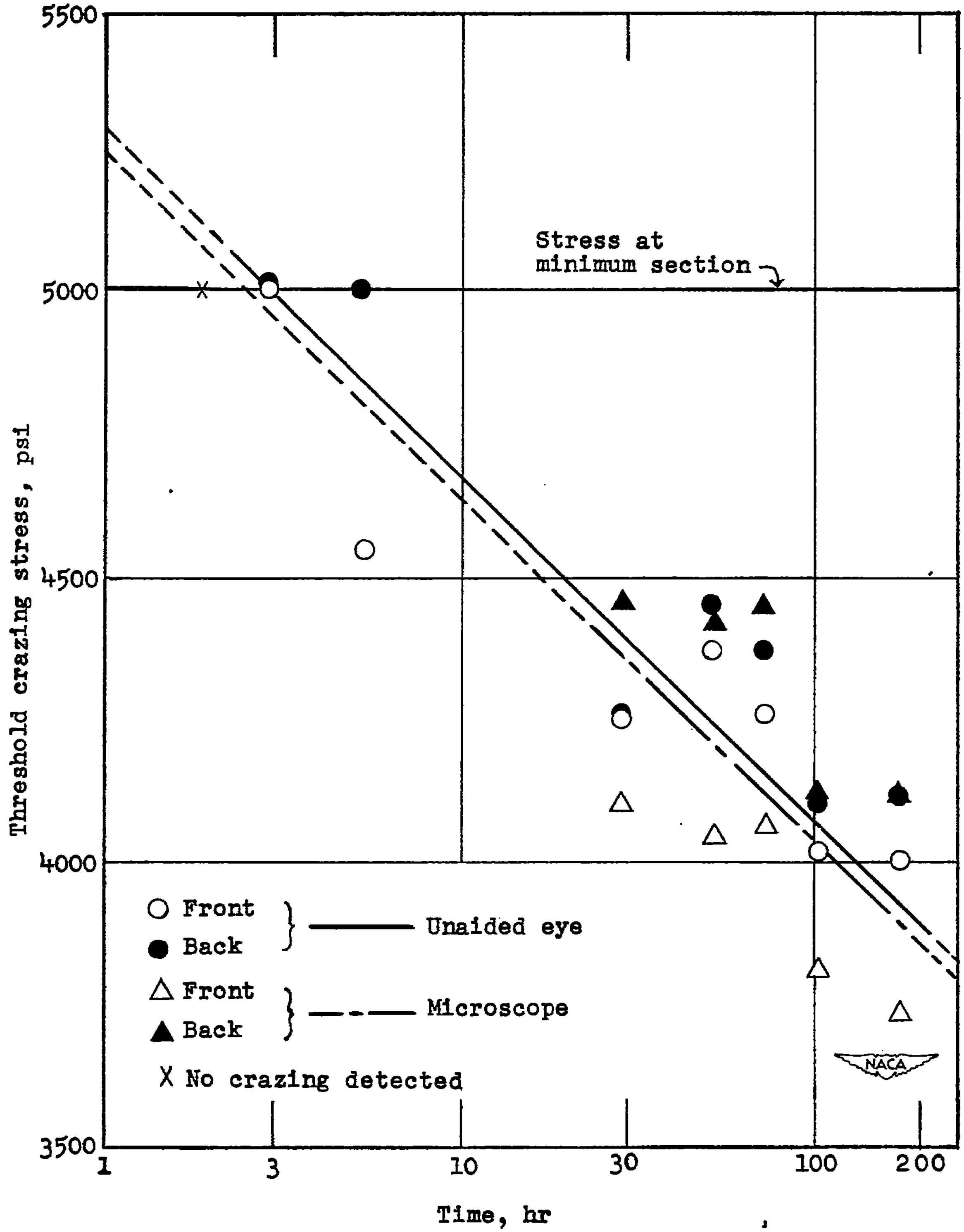

Figure 11.- A typical plot of threshold stress against logarithmic time obtained from long-time tensile-test data for unstretched specimen of sample P2a, tested at 50-percent relative humidity.

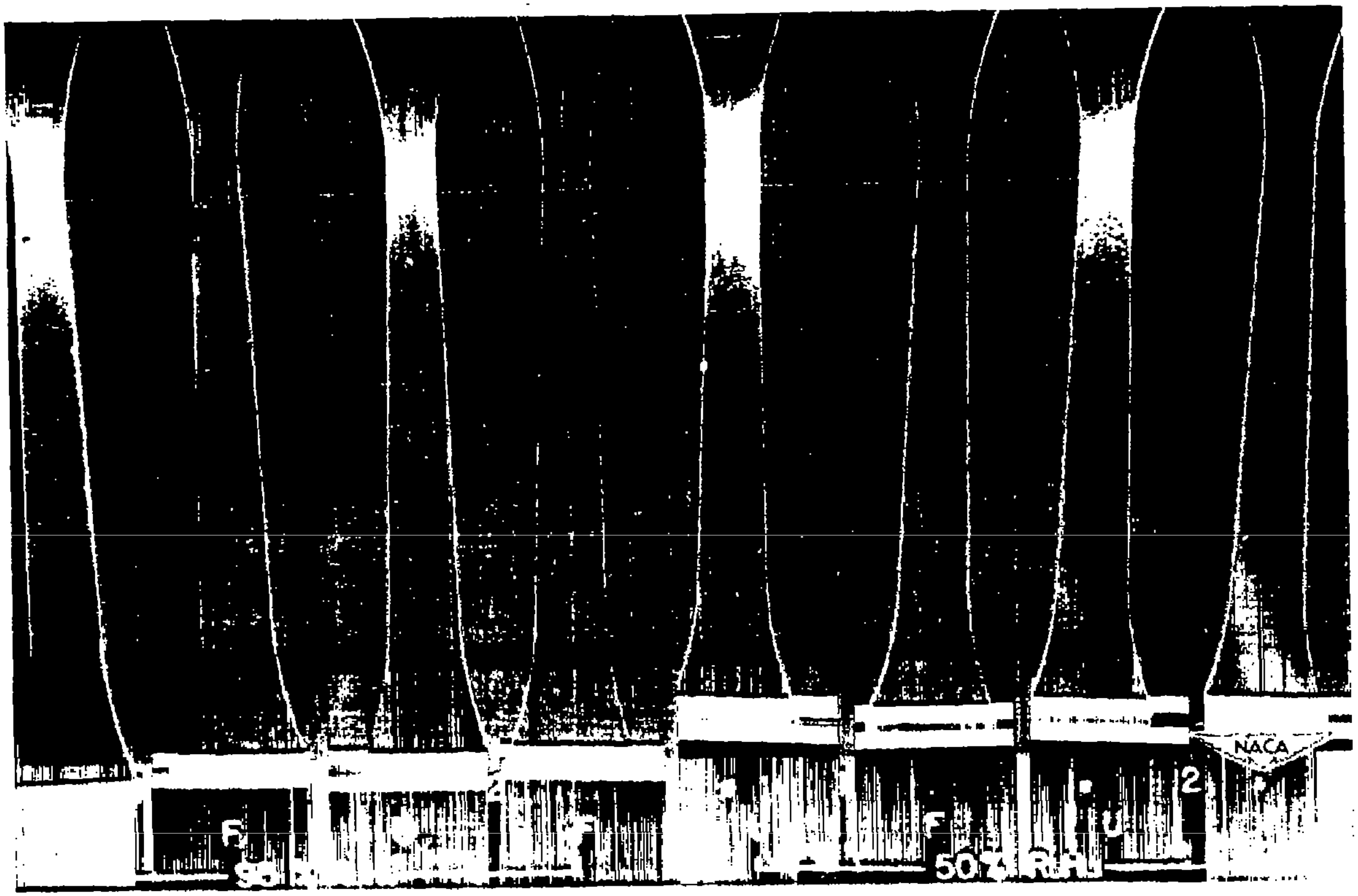

Figure 12.- Specimens from sample L1d, formed and unformed, after 6 days of tensile loading with 3750-psi stress at minimum section. Number on top line designates sheet from which specimen was taken. Letter designations are: U, unformed material; F, formed material; R.H., relative humidity.

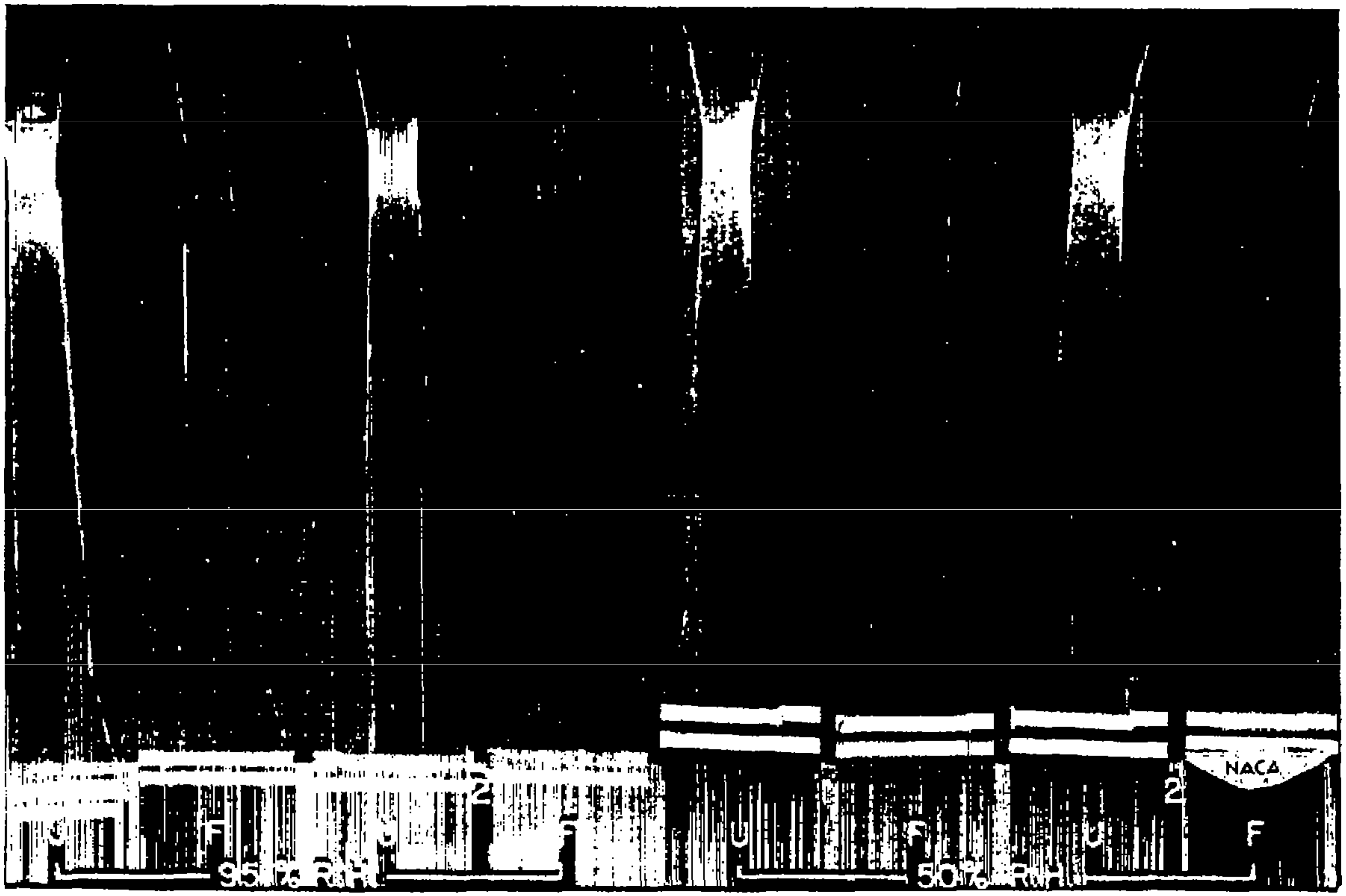

Figure 13.- Specimens shown in figure 12 after same test conditions but photographed with one-fourth of previous exposure. Number on top line designates sheet from which specimen was taken. Letter designations are: U, unformed material; F, formed material; R.H., relative humidity.

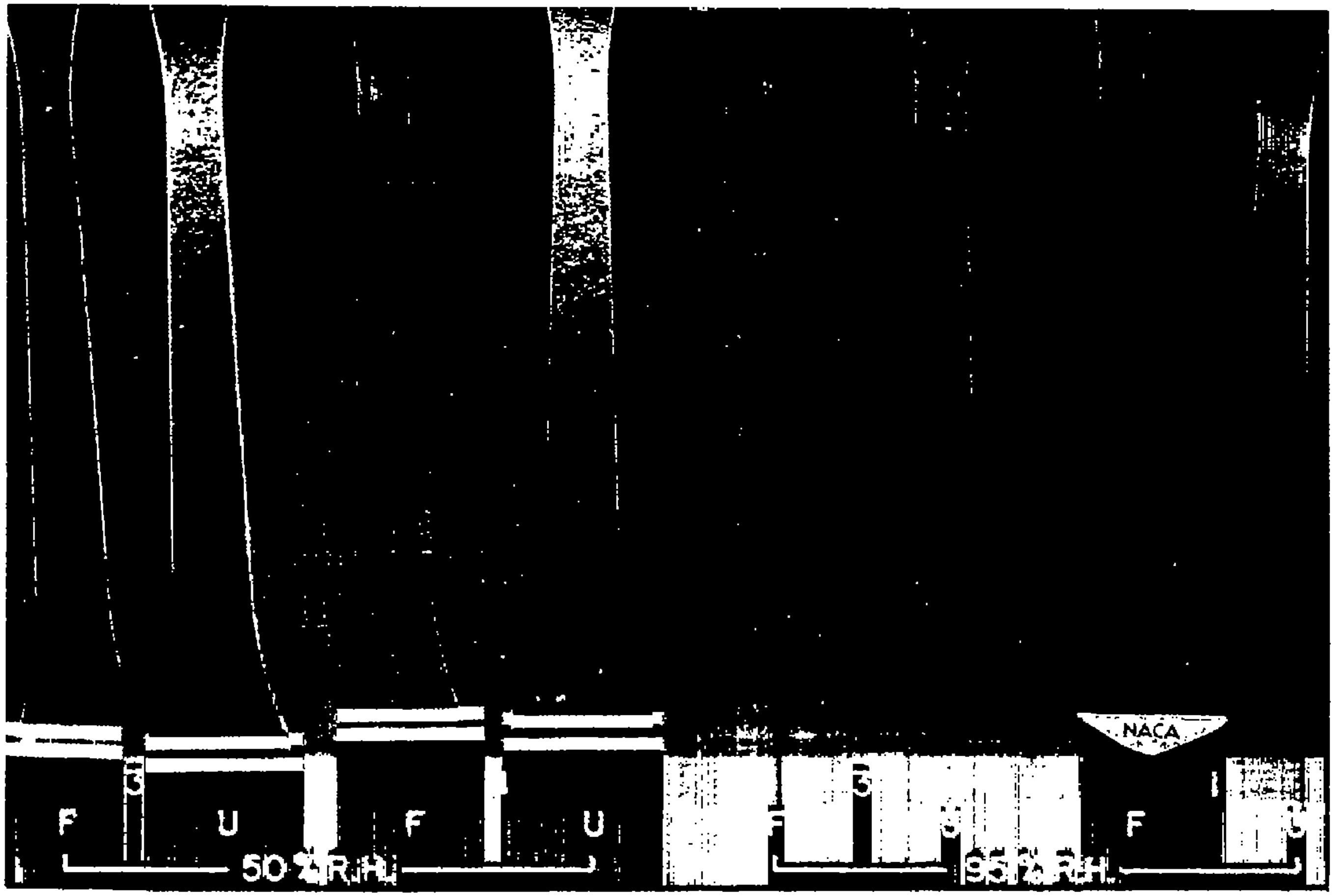

Figure 14.- Specimens from sample L2d, formed and unformed, after 4 days of tensile loading with 6000- and 5000-psi stress at minimum sections of formed and unformed specimens, respectively. Number on top line designates sheet from which specimen was taken. Letter designations are: U, unformed material; F, formed material; R.H., relative humidity.

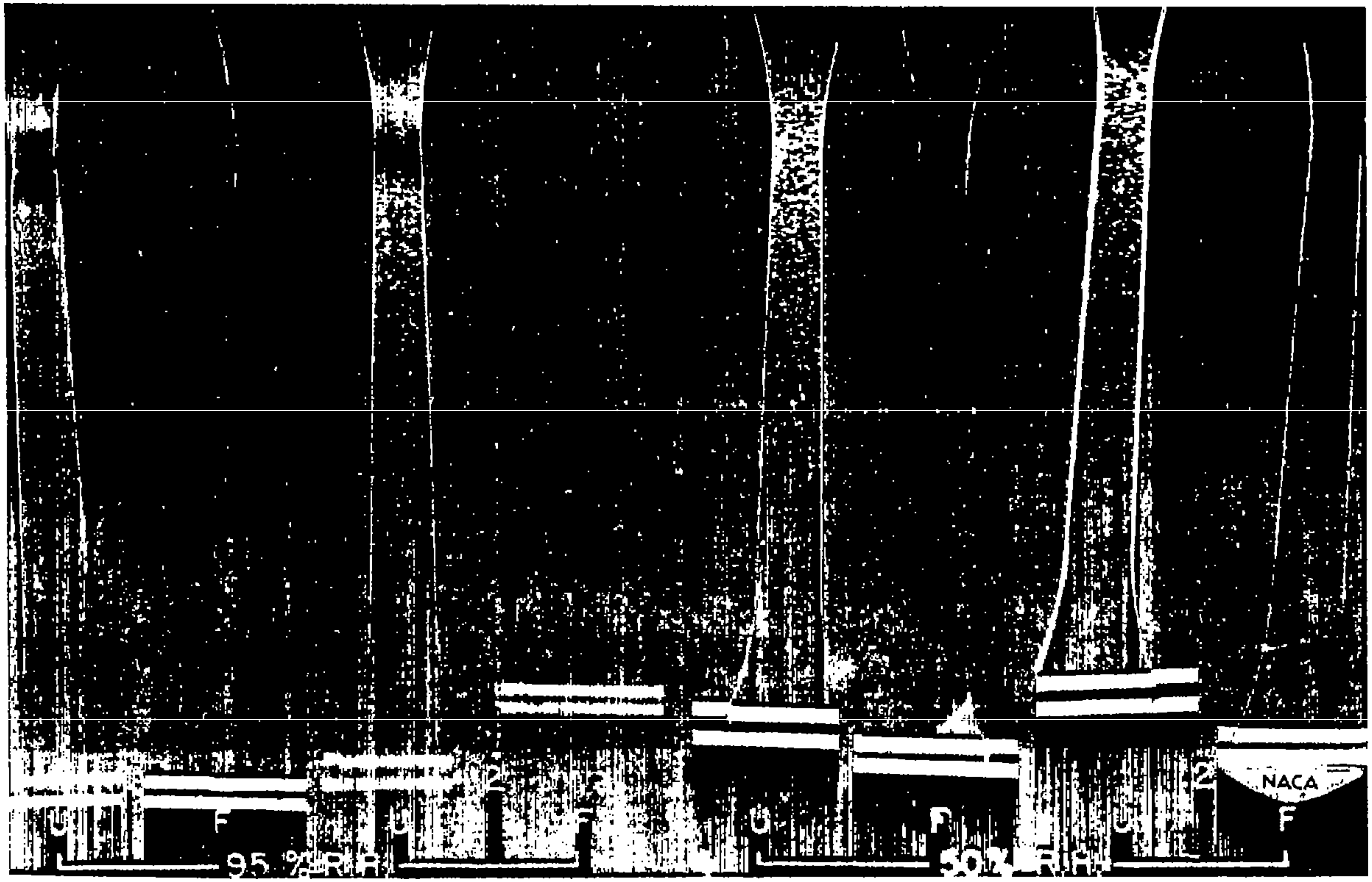

Figure 15.- Specimens from sample Pla, formed and unformed, after 7 days of tensile loading with 4000-psi stress at minimum section. Number on top line designates sheet from which specimen was taken. Letter designations are: U, unformed material; F, formed material; R.H., relative humidity.

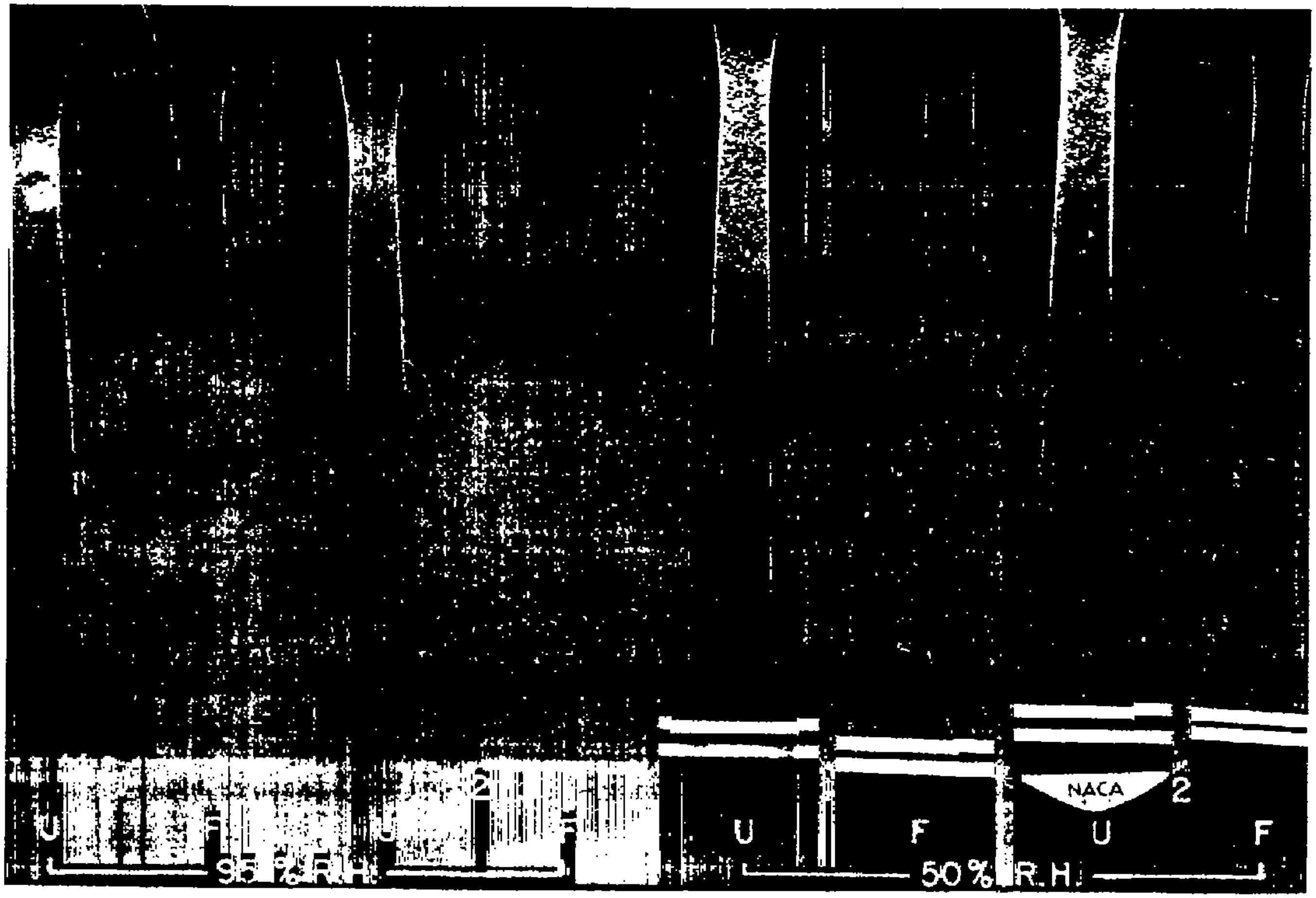

Figure 16.- Specimens from sample P2a, formed and unformed, after 7 days of tensile loading with 6000- and 5000-psi stress at minimum sections of formed and unformed specimens, respectively. Number on top line designates sheet from which specimen was taken. Letter designations are: U, unformed material; F, formed material; R.H., relative humidity.

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